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Driver Airbag Effectiveness as a Function of Velocity

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ABSTRACT

An investigation was conducted to estimate the effectiveness of airbags as a function of velocity. This study was conducted in two parts: field data using NASS-CDS and FARS and a computational process using both occupant simulations and CFD airbag models interacting with computational human surrogates. The field data indicates that airbags are most effective at low velocities: less than 40 kph and that airbag effectiveness goes to zero or becomes negative as the velocity increases for the unbelted occupant. The computational models of occupant interacting with an airbag indicates that as the velocity of the occupant with respect to the airbag increases the effectiveness of the airbag becomes very dependent on occupant initial conditions, trajectories and deployment times. As the velocity of the occupant becomes higher, for the airbag to be effective, the occupant motion has to be increasingly restricted; motion toward the center and perpendicular to the airbag. In addition, the airbag has to have deployed earlier. As a result only in limited conditions, for example a rigid barrier FMVSS 208 like test, is the airbag effective in "high" velocity impacts.

INTRODUCTION

On the surface, the effect of an airbag on an occupant during a vehicle crash may seem easy to understand. The airbag system places an inflated cushion between the occupant and other vehicle component. However, the airbag is a complex system in its nature and technology, which does not always lend itself to easy (if qualitative) categorization. It employs a high velocity injection of a gas into an unfolding airbag with continually evolving topology. Interactions with an occupant can occur during or after deployment and/or deflation. These interactions are associated with the chaotic nature of the gas dynamics and the airbag unfolding during the deployment process, the gas dynamics of the deflation and the energy absorption process, and the spacial-temporal effects entwined with the airbag history going from deployment to deflation - the results are not always intuitively obvious. Even if the properties and characteristics of the individual components and the nature of their interactions are reasonably well understood, the collective behavior of the ensemble can still defy simple explanation spanning the entire operational space. Therefore, it may not be possible to predict the response of an occupant in one vehicle crash by knowing the response of an occupant in an another crash of the same type but with different initial conditions.

For example, if we consider a vehicle running perpendicular into a rigid barrier at 48 kph, a FMVSS 208 test type, with an unbelted dummy interacting with a driver airbag. In general, the test will imply a high degree of effectiveness for the airbag. However, cadaver test data from sled tests, which mimic rigid barrier FMVSS 208 type, indicate that the airbag only restraint is significantly better than seat belt and better than airbag and seat belt combined (Kent et al., 2001). The implication is that belts degrade the performance of airbags and should not be used. This is opposite to real world experience, which demonstrates that belts are significantly better than airbags and that airbags and belts are the best option. Therefore, the effectiveness implied by the test is potentially misleading. Changing the test type or adding additional tests may not help in understanding or predicting the field.

Understanding effectiveness will have to come directly from field data. However, the effectiveness is multidimensional in its application. A subset of the significantly influencing factors, includes: occupant size, weight, sex, seating location and age; impact direction and location; vehicle size, mass, and structure; and vehicle velocity. Fundamental question on the enumeration of the effectiveness of airbags arises as a result of this complexity and the multiplicity of influential factors and their interactions. Consequently, perplexing features of the analysis landscape could result in erroneous interpretations. Care should be taken with the interpretation of the field data particularly when there is the possibility of co-factors and confounding factors. It may not be possible to get precise answers but instead only general trends.

Airbags have been reported to be effective in preventing fatalities by many studies, but the magnitude of these benefits varies greatly from study to study. The most recent studies on the airbag effectiveness in preventing fatalities in frontal crashes report effectiveness values that range from 31 % (Kahane, 1996) to 16 % (Levitt et al., 1999). Barry et al., (1999), considering also the severity of the crash, concluded that the airbag effectiveness is a decreasing function of the crash severity and "that the greatest improvement in the number of lives occurs in low severity crashes, with a 34 % reduction being the theoretical maximum".

However, fatal accidents are rare and unrepresentative of the majority of traffic accidents. Crashes with fatality account for only 0.5 % of all reported crashes and less than 2 % of reported crashes with injury (NHTSA, 1998). Determining research priority based only on fatal accidents can bias the study to consider only the most catastrophic accidents at the expense of potentially more common crash types, which are disabling (serious and greater injuries) but not necessarily fatal. This has been a rich area of investigation and many study have been published on the airbag effectiveness in reducing serious and greater injuries to specific body regions. Many of these studies indicate reductions in head and upper torso injuries among occupants in frontal crashes, but the effect spans a wide range (NHTSA, 1999, Deery et al., 1998, Langwieder et al., 1996, Pintar et al., 2000, Lund et al., 1996) and there is no clear indications of the effectiveness trend with respect to the severity of the crash.

The goal of this analysis will be mainly on one area: airbag effectiveness in reducing serious and greater injuries in frontal impact with respect to the severity of the crash. This analysis will provide effectiveness estimates of the driver-side airbag in reducing serious and greater injuries in frontal crashes as function of crash severity, while controlling for characteristics known to influence the injury risk such as seat belt use, age and sex of the driver, mass of the vehicles involved in the crash.

THE BEHAVIOR OF AIRBAG EFFECTIVENESS

The "airbag effectiveness" as used in this study and many similar studies is defined as the reduction in probability of certain mode of injury (or fatality) at a given severity with the presence of the airbag, relative to that without the airbag. That is:

(1) $$E(x) = \frac{P_n(x) - P_y(x)}{P_n(x)}$$

where $E(x)$ is the airbag effectiveness under the given crash severity, x denotes crash severity (i.e., velocity change), $P_y(x)$ and $P_n(x)$ denote the probability of injury (or fatality) with and without the airbag, respectively.

Based on field accident data analyses, the airbag effectiveness as defined above decreases as the severity increases. This may seem baffling, but is quite reasonable after some thoughts are given. The following discussion illustrates this.

To study the behavior of $E(x)$, we may take a look at its derivative:

(2) $$E'(x) = \frac{P_n'(x)P_y(x) - P_y'(x)P_n(x)}{P_n^2(x)}$$

The airbag effectiveness will decrease with an increase in x when its derivative is negative:

(3) $$P_n'(x)P_y(x) - P_n(x)P_y'(x) < 0$$

With this, we see that the variations of $E(x)$ can be quite complex, and it depends heavily on the behavior of the risk functions and their derivatives.

Given this, it is still possible to discuss the general behavior of the airbag effectiveness based on some general behavior of the risk functions and by examples. We start with the behavior of $P_y(x)$ and $P_n(x)$. These are generally monotonically increasing functions of x, for the type of physical phenomenon they are representing (i.e., the more "severe" the crash event, consistently the higher the injury probability). Secondly, at least conceptually (as opposed models), each of these starts from zero at some low crash severity (there is always crash low enough in severity that no injury will result); and each reaches 100 % at high enough severity. This is true even in the with-airbag case, because even with the airbag, injury or fatality will result when the crash is simply too severe. Figure 1 gives a schematic of this type of injury probability function.

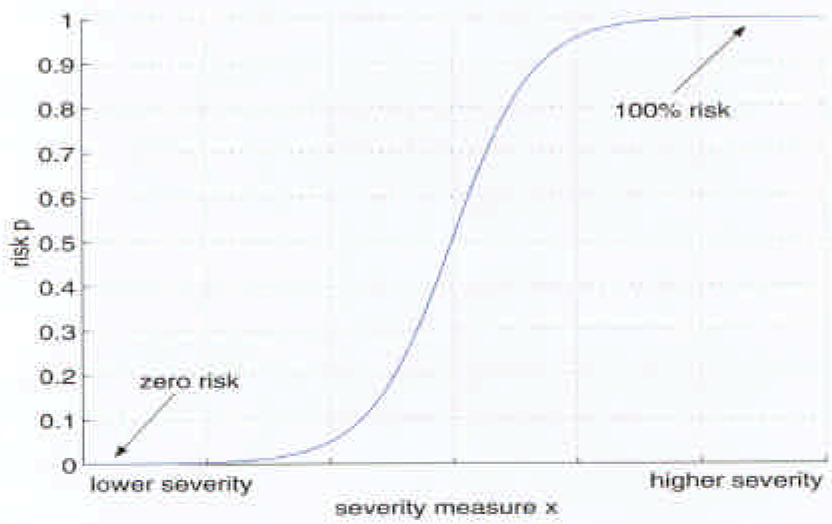

Figure 1. Schematic of the general form of risk function (with or without airbag).

Two characteristics of the airbag effectiveness function are quite straight forward, with the above discussion:

> *(i) Airbag effectiveness will start from a finite number between zero and one at sufficiently low severity.*
>
> *(ii) Airbag effectiveness will drop to zero for sufficiently high severity levels.*

This is because at sufficiently high severity, both with- and without-airbag cases have a risk of 100 %. Therefore, by definition, the effectiveness is zero. More characteristics of the airbag effectiveness function can be explored by more assumptions regarding $P_y(x)$ and $P_n(x)$. The first assumptions are about the form of these risk functions, they are assumed to be of the form:

(4) $$P(x) = \frac{1}{1+\beta e^{-\alpha x}},$$

where $\alpha > 0$, and β is such that it gives a near-zero $P(x)$ with a small value of x. This specific form is often used in modeling the no injury versus injury type of binary classification of injury risk.

> *(iii) The effectiveness generally is a decreasing function from 100 % to 0 %, when airbag simply gives a pure shift in the risk curve.*

A simple scenario of the effect of the airbag could be that it simply reduces the risk uniformly across the entire severity range. Such an effect can be represented as:

(5) $$P_y(x) = P_n(x + \Delta x) \,,$$

where Δx effective severity lowering effect from the airbag. Combining Equations 4 and 5, the behavior of the effectiveness is obtained under these assumptions, and it is shown in Figure 2.

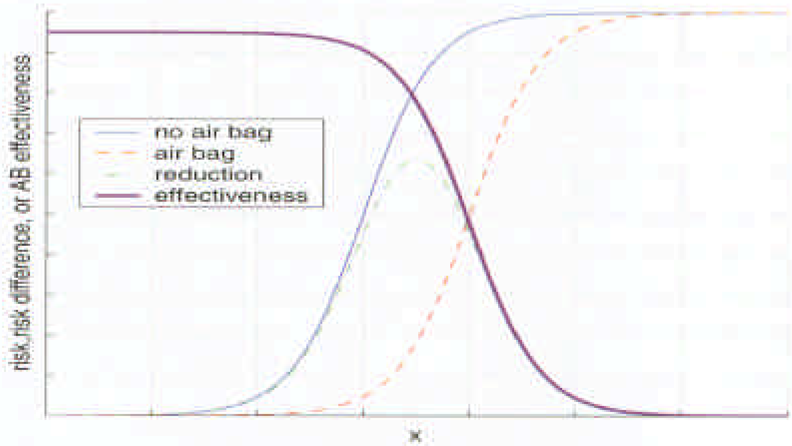

Figure 2. Example of effectiveness when airbag effect is a shift in risk curve.

(iv) The effectiveness is in general a decreasing function, from 100 % to 0 %, when airbag gives more reduction at lower severity range.

Such an effect can be modeled with a shift as that in (iii), with an additional increase in α in Equation 4. An example of this is given in Figure 3.

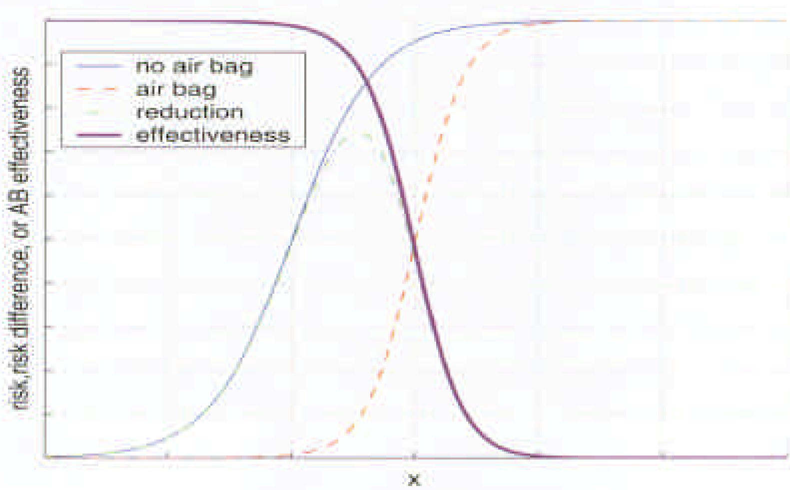

Figure 3. Example of effectiveness when airbag effect is a shift in risk curve and a larger effect in the lower severity range.

(v) *The effectiveness may assume a maximum in the middle of the severity range, and eventually decreases towards 0 %, when airbag gives more reduction at higher severity range.*

Such an effect may be modeled similarly to that in (iv), but with a decrease in α. An example of this is given in Figure 4.

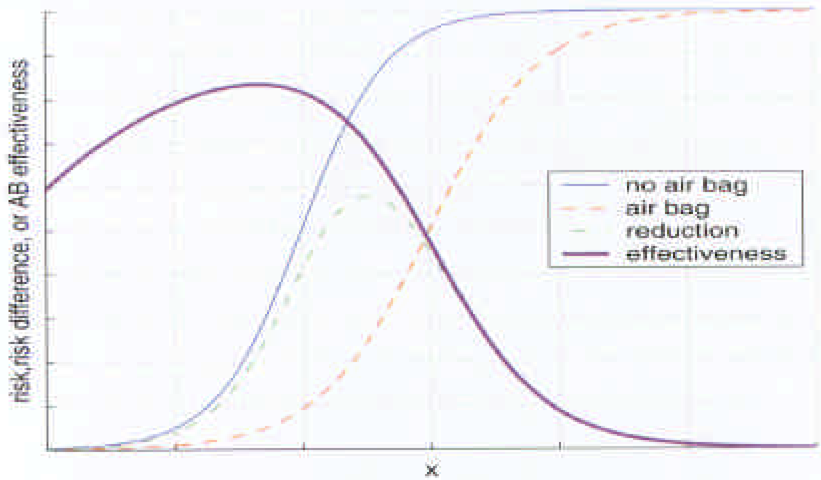

Figure 4. Example of effectiveness when the airbag effect is a shift in risk curve and a larger effect in the higher severity range.

Instead of using the log-sigmoid risk function form, another form that is the cumulative probability of a normal distribution is also used. The behavior mentioned in (iii), (iv), and (v) still holds.

In airbag effectiveness studies, often both the cases of serious injury and fatality are studied. If the effect of the airbag under each condition is a pure shift (as shown in Figure 2; and the difference between serious injury cumulative probability curve and fatality cumulative probability curve is also a pure shift (for with and without airbag cases), then the resulting airbag effectiveness curves for serious injury and fatality will also only differ by a pure shift. This is schematically depicted in Figure 5.

Figure 5. Schematic illustration of shift in airbag effectiveness curves between serious injury and fatality cases, when airbag gives a shift in the probability curve in each case.

Finally, in general, the true risk "curves" may not land themselves to a simple parametric representation, and they may not be sufficiently smooth. In certain severity ranges, for some physical reasons, the risk with the airbag may even be higher than that without (in which case the effectiveness will be negative).

To summarize, this discussion shows that in general, the airbag effectiveness is expected to start with a finite number and drop to zero, in the full range of crash severity normally of interest. The behavior between these extremes can be quite complex, due to the way in which it is defined. It depends on the relative magnitude of the two risk functions, and their functional form. In some cases, negative effectiveness is possible. It is the case when the airbag effectiveness curve exceeds the no airbag effectiveness curve.

NON PARAMETRIC ESTIMATION OF AIRBAG EFFECTIVENESS USING NASS

A NASS study of likelihood of driver serious injury (AIS3+) in purely frontal crashes has been conducted primarily to assess the effectiveness of airbag in such impact mode. Airbags have demonstrated significant effectiveness in protecting occupant's head during the frontal crashes ([Exhibit 11] NHTSA, 1999). This analysis focuses on the benefits airbag provides to head in terms of reducing serious injuries and fatalities caused by head colliding with a hard surface at the absence of airbag. This effectiveness measure is demonstrated as a function of impact velocity or delta-V. This study aims to establish the injury trends among two sets of crashes in which the direction of force is determined as 12 O'clock or purely frontal: 1) when the airbag deployed during the crash, and 2) when either the vehicle was not equipped with airbag, or the airbag did not deploy (for crashes below the airbag deployment threshold or malfunction of the airbag triggering mechanism). In each of the above condition, additional restraint control is placed among the occupants seat belt usage.

The analysis data is compiled from 1993 to 1999 NASS/CDS database. The stratified data frequency from this database with the assigned weighting factor for each record is used in order to reflect national projections. This study examined the risk of AIS 3+ injury per 100 exposed drivers in 2 mph velocity bins. To compare the results among different restraint modes, the data was normalized. The "rates", defined as the ratio of number of exposed drivers in a particular impact velocity bin who sustained serious injury by the total number of exposed drivers for the same velocity bin, are obtained. Moving average technique has been applied to the total observations for each impact velocity bin to compensate for the unavailability of data in certain velocity bins.

Results and Discussion

The focus of this study is the restraint use and its influential association with reduction in injury risk for drivers in frontal impacts. For the purpose of effectiveness measures of airbag for belted drivers compared to unbelted drivers, the injury risk is examined separately for each of these groups. Figure 6 shows the injury risk of drivers protected by airbag only, compared to the cases when the driver is not protected by any type of restrains. The airbag lowers the risk of serious injury for unbelted drivers for low to mid range impact velocity up to about 25 mph. On the other hand, for higher speeds, the airbag increases the risk of serious injury for drivers. Whereas, Figure 7 indicates that the injury rates are relatively lower at all impact velocities when the driver is protected by airbag and belt combined compared to when protected by seat belt only. However, the airbag effectiveness in protecting belted driver's head will reduce at high impact velocities.

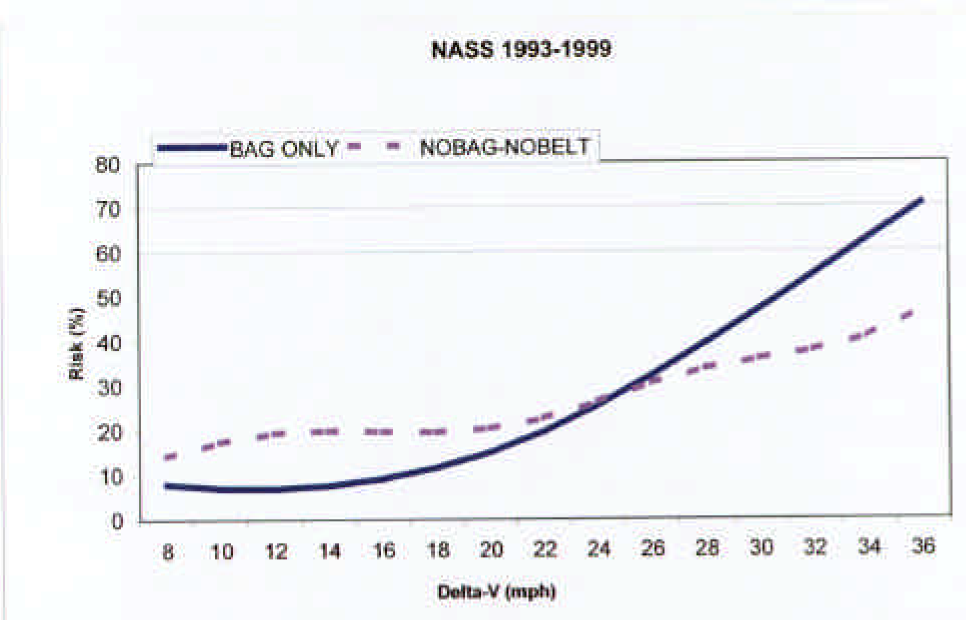

Figure 6. Influence of airbag on driver head injury – Unbelted.

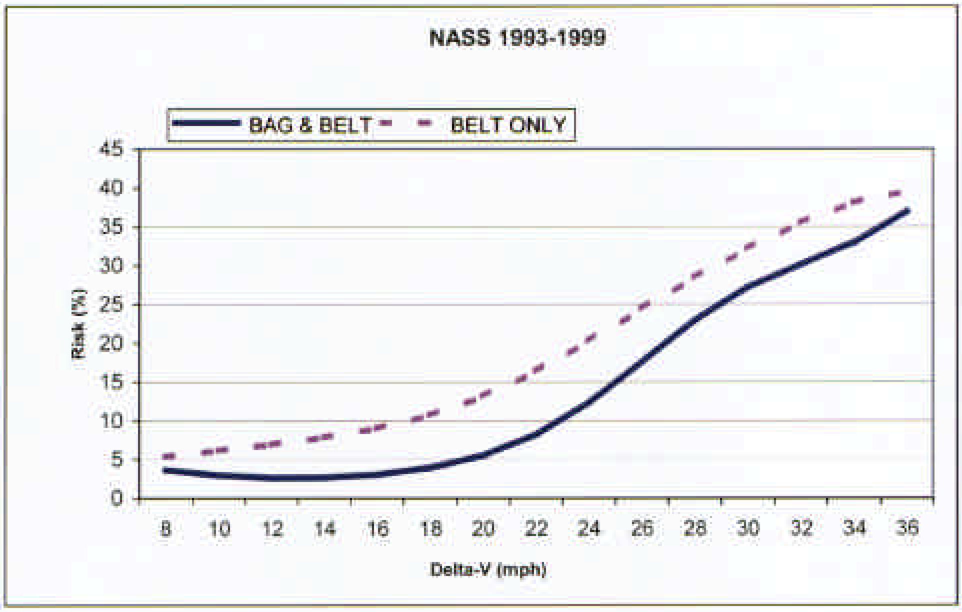

Figure 7. Influence of airbag on driver head injury – Belted.

The effectiveness is computed using Equation 1. The computation is done separately for belted and unbelted drivers. Figure 8 illustrates that significant injury reducing potential of airbags for belted drivers. The benefits of airbags for unbelted drivers are realized at low delta-V speeds and it starts loosing its effectiveness and drops to minimal effectiveness around 25 mph, and actually is not effective after that.

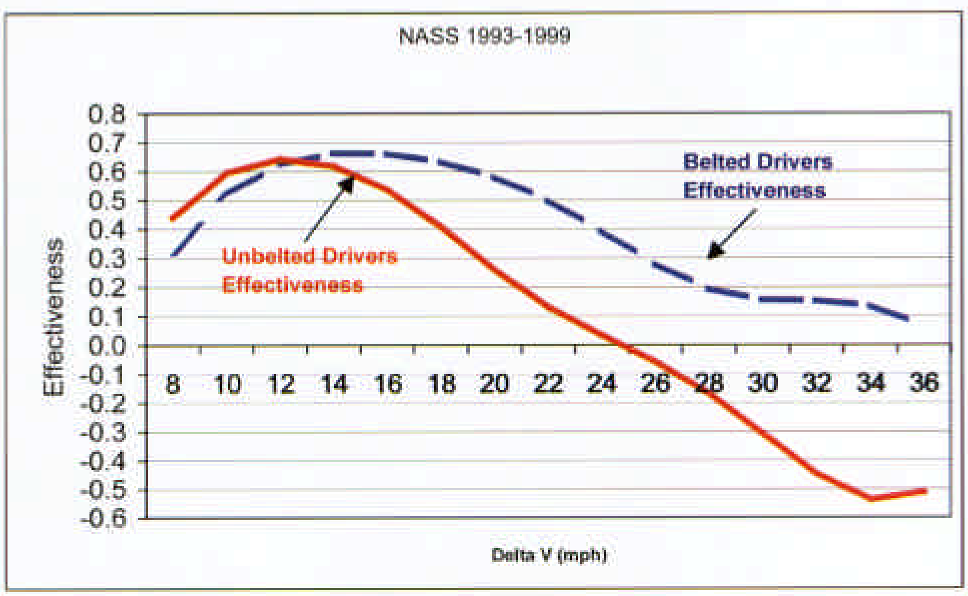

Figure 8. Airbag effectiveness in injurious frontal crashes.

LOGISTIC REGRESSION ANALYSIS USING NASS

The non-parametric analysis described in the previous section provides an estimate of the airbag effectiveness that has some limitations. The main limitation with the approach is that it can only control the effect of additional factors, such as age of the driver or mass of the vehicle, through further data restriction. Thus, limiting the sample data and reducing the significance of the results, unless a very large number of cases are available for the analysis which is not the case here.

In this section, a parametric (logistic regression) analysis will be performed using NASS-CDS data. This approach allows control of both effects of confounder and modifier factors but, on the other side (drawback), it will assume a specific shape for the risk function. The assumed shape is an approximation of a normal distribution which is considered the best approximation when the shape is not known.

Data and Method

The data were extracted from the NASS-CDS database for the calendar years 1993 through 1999. The analysis was restricted to only frontal crashes since from previous studies (Barry et al., 1999, Kahane, 1996) airbag effectiveness has been demonstrated only for this crash mode. The more the crash diverts from the pure frontal impact the less effective the airbag will be, up to when it is not effective at all (Kahane, 1996, Barry et al., 1999). We restrict our analysis to passenger cars of model year later than 1988 because the body structure and the crash performance of old vehicles could be too different from that of newer vehicles. The data inclusion criteria for this analysis entailed being the driver of a car model year later than 1988 involved in a frontal crash (direction of force between 11 and 1 O'clock).

The effectiveness of airbags in reducing serious injury was evaluated with the Abbreviated Injury Scale (AIS). The most severe injury sustained by an occupant is referred to as the Maximum Abbreviated Injury Scale (MAIS) score. The data were analyzed by applying the logistic regression method. The outcome variable was a dichotomous variable indicating whether the driver sustained a serious injury (MAIS $\geq$ 3), or minor/no injury (MAIS $\leq$ 2).

A forward stepwise procedure was used for the modeling strategy. We consider the following parameters for inclusion: driver's age, airbag deployment, safety belt use, severity of the crash, mass ratio between the two vehicles involved in the crash (i.e. mass-of-the-subject-vehicle/mass-of-the-collision-partner), and all the meaningful interaction terms between them. The list of all the variables used and their levels are shown in Table 1. All the terms that retained statistical significance were included in the final model and a summary of all the parameters included in the model and their estimated values are shown in Table 2.

Table 1. VARIABLES USED IN THE LOGISTIC REGRESSION ANALYSIS.

Variable	Levels used
Delta-V	10 – 15
	16 – 20
	21 – 25
	> 25
Age	< 25
	25 – 54
	≥ 55
Airbag	Not deployed / Not available
	Deployed
Seat Belt	None / Not used
	Seat belt used
Mass Ratio	< 0.6
	0.6 – 1.0
	> 1.0

Table 2. PARAMETER ESTIMATES FOR THE LOGISTIC REGRESSION MODEL. THE ":" OPERATOR REPRESENTS AN INTERACTION.

Variable	Parameter Estimate
Intercept	2.4214
Delta-V	-0.0698
Age	-0.4256
Airbag	3.0526
Seat Belt	0.7435
Mass Ratio	1.6542
Airbag : Seat Belt	0.393
Airbag : Delta-V	-0.0704
Airbag : Mass Ratio	-0.7416
Delta-V : Mass Ratio	-0.0414

Results

This study confirms that the probability of serious injury is an increasing function of age (see Table 2) but, from a preliminary study, the airbag effectiveness was the same for every group age.

A significant difference in the effectiveness of airbags for belted and unbelted drivers were detected. The airbag was found more effective for belted than for unbelted drivers. Figures 9, 10, and 11 show that the airbag effectiveness is a decreasing function of the crash severity and its effect depends on the mass of the cars involved in the collision. In all figures, the effectiveness function has been clipped at the zero value. In other words, an effectiveness value of zero and below has been plotted as zero effectiveness.

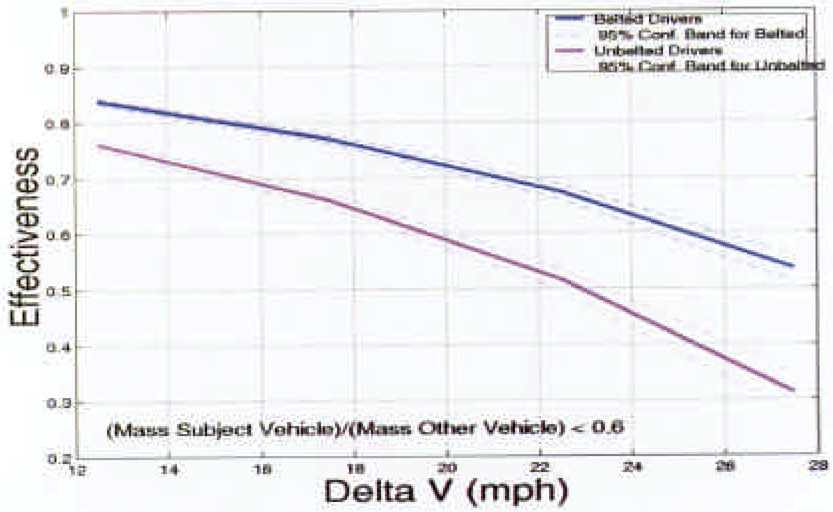

Figure 9. Airbag effectiveness in reducing serious injuries when the driver is travelling in the lighter vehicle.

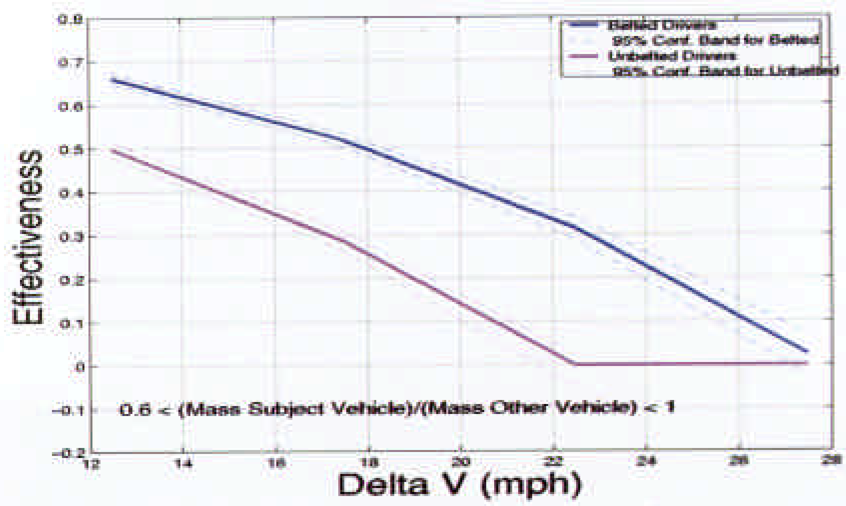

Figure 10. Airbag effectiveness in reducing serious injuries when the two vehicles involved in the crash are of similar mass.

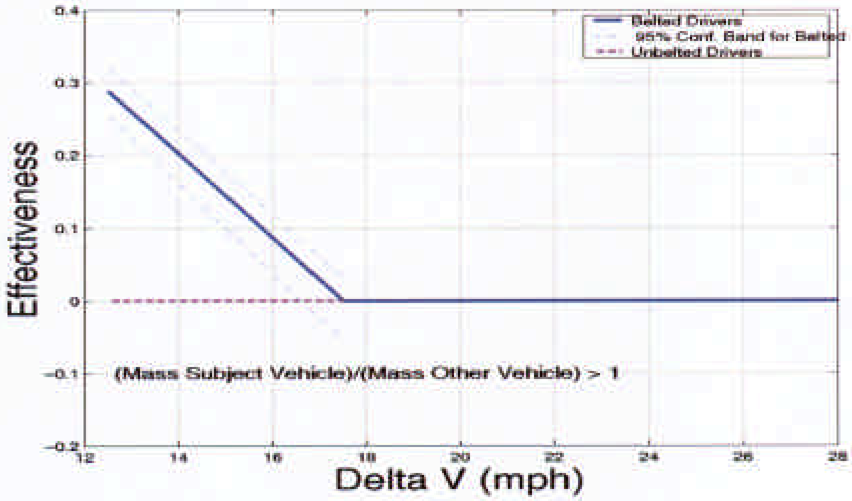

Figure 11. Airbag effectiveness in reducing serious injuries when the driver is travelling in the heavier vehicle.

Figure 9 shows that when the driver is traveling in the lighter car, with respect to the collision partner, the effectiveness of the airbag is decreasing but still positive for the range of crash severity.

When the two cars involved in the frontal crash have approximately the same mass and the driver is belted, the airbag is effective in reducing serious injuries, at any crash severity, even if its effect is almost negligible for the most severe crashes. For unbelted drivers the airbag effectiveness is strictly decreasing and positive only up to 22 mph, for more severe crashes the airbag does not show any effectiveness (see Figure 10).

For unbelted drivers, traveling in a vehicle heavier than its collision partner, the airbag is never effective (see Figure 11). For belted drivers the airbag shows a limited effect only at low speeds. It seems that the effect of the mass is completely offsetting the airbag effectiveness.

Discussion

The airbag was found more effective for belted than for unbelted drivers. This result does not agree with the results reported in some previous studies based on FARS (Barry et al., 1999, Kahane, 1996) in which the airbag was found to be less effective for those already wearing a seat belt. Nevertheless "The consensus is that FARS does not necessarily contain accurate information about the belt use of crash survivor, especially in recent years" (Partyka, 1988). More precisely, "the quality of belt use data in FARS is only reliable as the quality of information from police accident reports. Some states, such as California, do not even provide space for recording belt use. ... Also in many cases in FARS, belt use is guessed at or taken from reports of those involved in crashes, not from first hand observation by the police officer." (Evans, 1986).

Moreover, in the Barry et al., (1999), study, the differential effect of the airbag for belted and unbelted drivers is not statistically significant. In fact, they write: "... a significant airbag and belt use interaction was not detected in this study, this has been reported by previous studies and such interaction might reasonably be expected. Thus it is possible that such interaction exists but current FARS data are inadequate to detect it."

As shown in this study, it is reasonable that the airbag deployment offers more protection when the seat belt is in use. The main purpose of the airbag is to protect the head of the driver and this is not feasible if the driver is sitting such that his/her head is out of position. Unbelted occupants may be out of position when the airbag deploys because of pre-crash braking or pre-crash maneuvers, and as result they may be outside the protective envelope of the airbag or too close to it for optimal protection. The seat belt forces the driver to be seated in a controlled position with respect to the airbag module, so that the effectiveness of the airbag itself is maximized.

This analysis emphasizes the different effect of airbags across the severity of crashes. The statistical significance of the negative interaction between delta-V and airbag deployment gives support to the proposition that airbag effectiveness decreases as the crash severity increases. This result could be analytically proven the only possible trend of the airbag effectiveness as function of the crash severity (see section "The Behavior of Airbag Effectiveness"). Moreover, a similar result has already been presented in previous studies like Barry et al., (1999), and NHTSA, (2000), based on FARS data. A detailed discussion on the Barry et al., (1999), study is reported in the following section.

Moreover, this study suggests that the airbag effectiveness declines as the mass of the vehicle increases with respect to the other vehicle involved in the crash. The same trend has been already suggested for the seat belt effectiveness by Malliaris et al., (1995). In their study, Malliaris et al. reported that the airbag deployment among old cars (NASS-CDS 1988-1992) is highly non-uniform with respect to the car mass. This implies that in older studies the airbag effectiveness could not been estimated as function of the car mass. This is primarily due to the non-uniform distribution of airbag among the subject cars and to the small number of available cases.

AIRBAG EFFECTIVENESS ESTIMATION BASED ON FARS DATA

The study described in this section is based on the work of Barry et al., (1999). This study includes data from the U.S. FARS database for the years 1991-1995 (inclusive). The analysis was restricted to pure frontal collisions of passenger vehicles. Only front seat passengers were considered in the analysis. The data have been analyzed using conditional logistic regression. Barry et al., (1999), reported their estimation of airbag effectiveness in terms of probability of death in potential fatal crashes P_{pf}. To translate the results presented in the paper in terms of crash severity is not straightforward. Following the rationale suggested by the authors we will estimate P_{pf} with:

$$(7) \qquad P_{pf} = \frac{Fatalities}{\frac{1}{3}\ MAIS\,3+},$$

Barry et al., (1999), consider their estimates of airbag effectiveness "overestimates relative to the population of fatal crashes". For this reason, a possible lower bound for the airbag effectiveness curve will be introduced. An upper bound for P_{pf} is needed to estimate for a lower bound for the effectiveness. An upper bound for P_{pf} can be estimated by one of the two following expressions:

$$(8) \qquad U_1 = \frac{Fatalities}{\frac{1}{4}\ MAIS\,3+},$$

or

$$(9) \qquad U_2 = \frac{Fatalities}{MAIS\ 4+},$$

We estimated P_{pf}, U_1 and U_2 using NASS-CDS (1995-1999) data. We denote by L_1 and L_2 the effectiveness curves evaluated using U_1 and U_2, respectively. For this data L_1 and L_2 showed to be very close to each other at every speed. More precisely, L_1 was slightly above L_2 for speeds below 30 mph, they intersected at 30 mph and L_1 was slightly below L_2 for speeds above 30 mph. A lower bound for the effectiveness has been defined as:

$$(10) \qquad L_b = \min(L_1, L_2)$$

The estimated airbag effectiveness and its lower bound for different values of delta-V are showed in Figure 12. It is important to emphasize that caution should be exercised in extrapolating airbag effectiveness values from this plot. As already mentioned Barry et al., (1999), presented their results (based on FARS data) in terms of "probability of death in a potential fatal crash", we translated them in terms of crash severity using NASS-CDS data. This procedure is not straightforward and this implies that the estimation of P_{pf} could be subject to errors that will influence the decreasing rate of the effectiveness curve. In conclusion, Barry et al., (1999), study shows that in pure frontal impact, the airbag effectiveness in reducing fatalities reaches its maximum of 31 % for very low severity crashes and it decreases as delta-V increases but its exact decreasing rate cannot be estimated with high confidence.

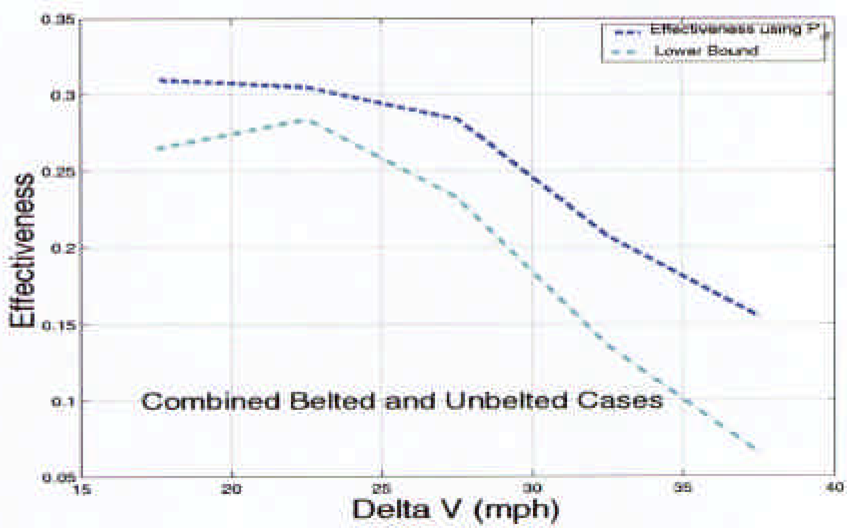

Figure 12. Revisit of the Australian National University study. Airbag effectiveness in reducing fatalities in pure frontal collisions.

It is not easy to compare the effectiveness rate based on Barry et al., (1999), study with our analysis (of the previous section) for two reasons. First, the Barry et al., (1999), study evaluated the airbag effectiveness in preventing fatalities while we focused on the airbag effectiveness in preventing serious injuries. Thus, comparison between Figure 12 with any of our results shown in Figures 8, 9, 10, or 11 should be made in light of the discussion of Figure 5. Second, the lack of confidence in the decreasing rate of the effectiveness curve plotted on Figure 12 prevents us from performing a more refined comparison of the effectiveness values. The statistically significant finding, of both analyses, is the decreasing effectiveness of airbag (in preventing either fatalities or serious injuries) as the crash speed is increasing.

NUMERICAL ANALYSIS – BAG AND BALL

Careful examination of the 12 O'clock frontal crash reveals that the crash typically has offset with variable overlap frontal crash area, implying that the occupant might not be in the 208 position and may be at an offset from the center of airbag at the time of impact. This study is trying to give an insight or a possible explanation of the airbag effectiveness demonstrated in the field data by numerical simulations of a simple model. With this simple model, we study the effects of impact velocity, occupant offset and sitting positions on the airbag effectiveness, while requiring reasonable computer and manpower.

Model Setup

As schematically shown in Figure 13, the model has a folded airbag attached to the rigid plane, and a freely moving rigid ball with mass of 3.67 kg to mimic 5 %tile female dummy's head. The coordinate system of the model is shown in Figure 13. The x-axis in the model is parallel to the longitudinal centerline of vehicle, the y-axis in the model parallel to the IP, and the invisible z-axis pointing toward the depicted cross section to form a right hand system. Three parameters are varied in this analysis, namely the ball initial velocity V_o, the initial distance between the ball and the airbag d, and the ball horizontal offset from the center line of the airbag measured as percentage as l/r Here r is the radius of the unfolded airbag. The initial velocity V_o represents the relative velocity between the occupant head and the airbag. Gravity is not included in the model.

After interaction with the airbag, the ball separates and travels with a constant velocity $\vec{V}^b$ called bounce back. Its y-component V_y^b is called bounce back lateral velocity or simply lateral velocity when there is no cause for confusion. The ratio V_y^b/V_0 indicates how fast the airbag pushes the ball to the side, and how hard it may strike the vehicle's left side structures. Hence, the ratio V_y^b/V_0 may be used as a surrogate to airbag effectiveness. Increase in the ratio V_y^b/V_0 translates to a reduction in the airbag effectiveness. For $V_y^b/V_0 > 1$, the airbag may pose more risk than protection.

Thus, we study the trends of the ratio V_y^b/V_0 as a function of the initial velocity, the distance d, and the offset l/r. Noting that all other parameters such as airbag geometry, inflator characteristics, material properties, contact parameters, etc. are maintained unchanged.

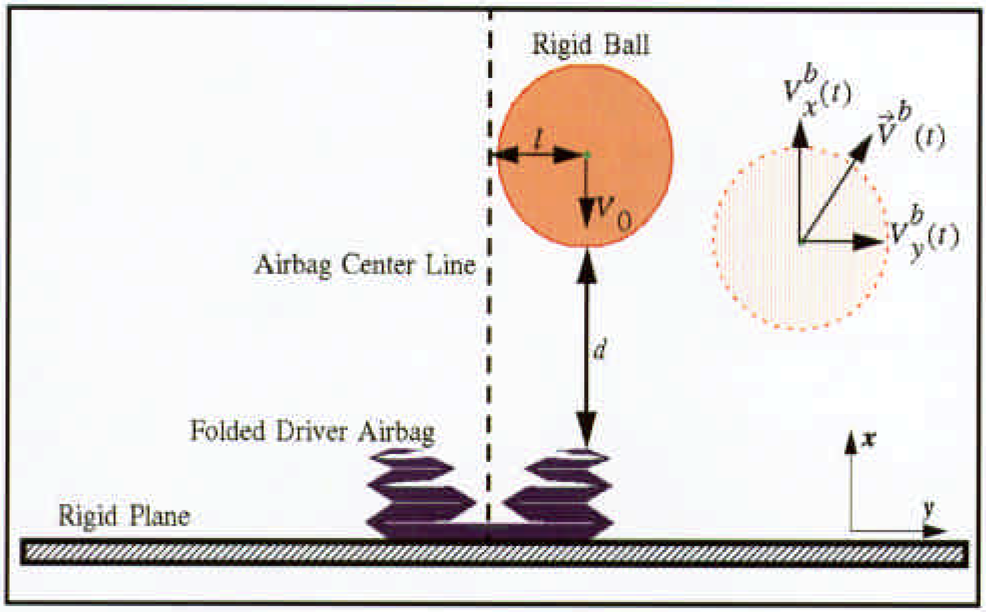

Figure 13. Schematic of the model setup for the numerical study.

Approach

Two different commercial software namely TNO Madymo and MSC Dytran are used for the numerical simulations. In Madymo simulations, the gas inside the airbag is treated as uniform in space, i.e. the fluid thermal properties such as pressure and temperature are everywhere the same. They are only function of time.

In Dytran simulations, Computational Fluid Dynamics (CFD) modeling of the airbag is used, i.e. the fluid velocity and thermal properties are not only functions of time t, but also functions of space (x, y, z). The CFD computational domain which covers the unfolding of the airbag during deployment is modeled with a uniform grid of $\Delta x = 0.01$ m, $\Delta y = \Delta z = 0.02$ m for a total of 49000 cells. The inflator is modeled as a ring in the bottom of the airbag attached to the support with an inner and outer radii of 0.037 m and 0.05 m., respectively The inflow in the inflator is in the x-direction.

In both modeling, the airbag self-contact with penalty methods is used. The self-contact parameters for the airbag are carefully controlled to minimize self-penetration. The contacts between the bag and the ball, and the bag and rigid plane are also defined. Since Dytran and Madymo use different input for contact parameters, an alternative method was developed as a starting point for the comparison. We used the Dytran uniform pressure model to match the Madymo results in one baseline simulation by varying the contact parameter between the bag and rigid parts. The contact parameters are then maintained and we proceeded by varying the initial velocity V_0, the initial distance of the ball d, and the horizontal offset l/r.

Results and Discussion

Figure 14 shows snapshots of the simulation for the case with a ball initial velocity of 10 mph, initial distance of 10 cm, and 30 % initial horizontal offset from the airbag centerline. It clearly demonstrates that the airbag pushes the ball sideways in the positive y-direction. This is primarily due to the initial offset of the ball.

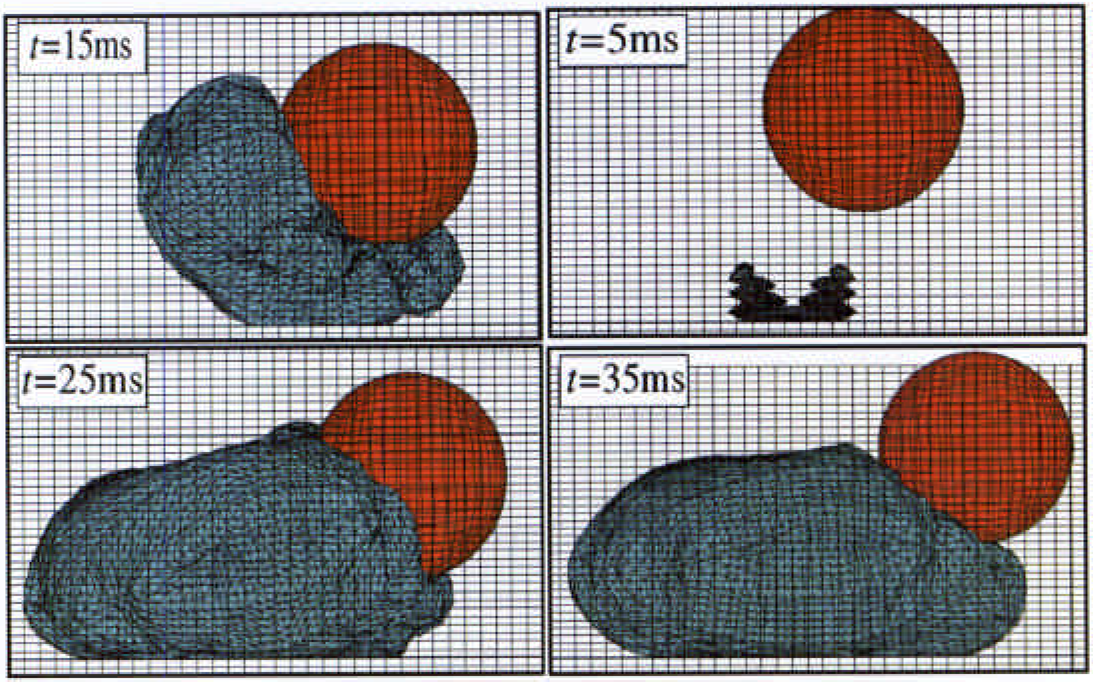

Figure 14. Snapshots of the ball and airbag interaction simulated with CFD modeling of airbag at different times.

Figure 15 shows the variation of the lateral velocities, relative to the initial velocity, as a function of initial velocity with fixed 30 % offset and initial distances of 20 and 30 cm for both uniform pressure and CFD modeling. For the initial distance of 20 cm, the CFD gives higher prediction than the uniform pressure model, while the results are very comparable for the initial distance of 30 cm. All curves show that the lateral velocity increases with the initial velocity, which implies that the airbag effectiveness reduce as the impact velocity increases. For a given initial velocity, the lateral velocity decreases as the initial distance increases, which implies that the farther from the airbag the occupant is, the better off he/she is.

Figure 15 also shows the results for the initial distance of 10 cm for the uniform pressure model. As noted earlier, the closer we get to the airbag, the higher the difference between CFD and uniform pressure modeling. In this case, that would have rendered the plot out of scale. Note that this difference between CFD and uniform pressure modeling is purely in magnitude, the other characteristics being of similar trends. The drop in the initial distance of 10 cm after about 15 mph is quite expected since there is a finite amount of energy in the airbag. Similar behavior would be expected for the initial distances of 20 and 30 cm at higher delta-V.

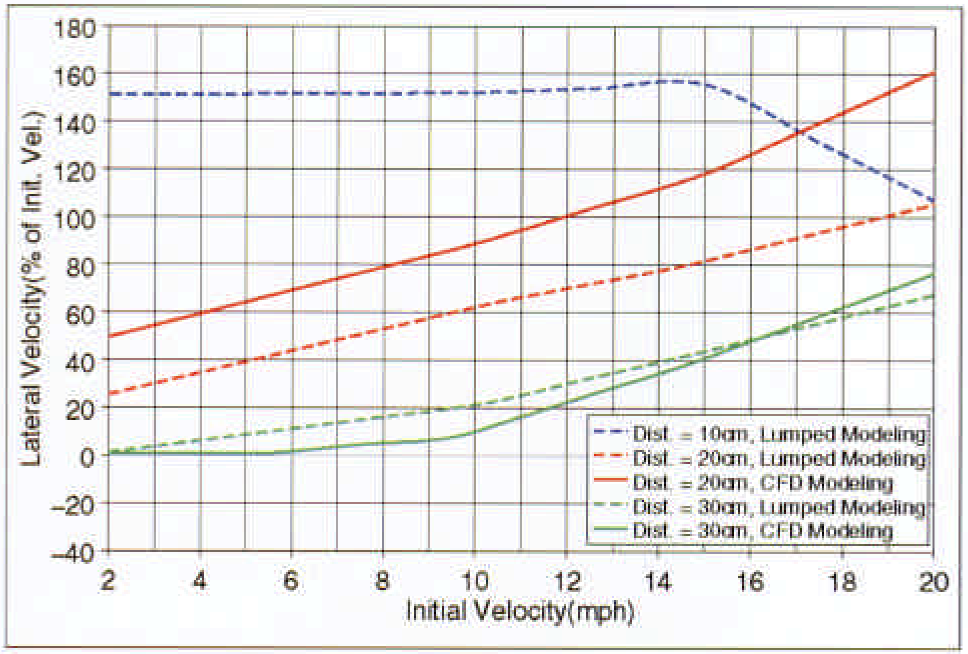

Figure 15. The comparison of lateral velocity relative to the initial velocity. The ball has 30 % initial offsets from the centerline of the airbag.

Figure 16a shows the lateral velocities relative to the initial velocity as functions of initial velocity for fixed initial distance of 20 cm and varied offsets predicted with the uniform pressure model. Figure 16b shows similar results from the CFD modeling. The two modeling techniques give similar trends with higher values for the CFD modeling. Both figures show that the ratio of the lateral velocity to the initial velocity increases as the initial velocity increases. This ratio exceeds 100 % at high velocities and offsets. The figures also show that, at a fixed initial velocity, the lateral velocity increases as the offset increases. This indicates that the airbag effectiveness might reduce as the offset increases. In summary, the ratio of lateral velocity to the initial velocity increases as the initial velocity increases, the initial distance decreases, and as the initial offset increases. This implies that the airbag is more effective when the occupant sits further away from the airbag, when the occupant is more inline with airbag (less lateral offset), and when the impact velocity is lower.

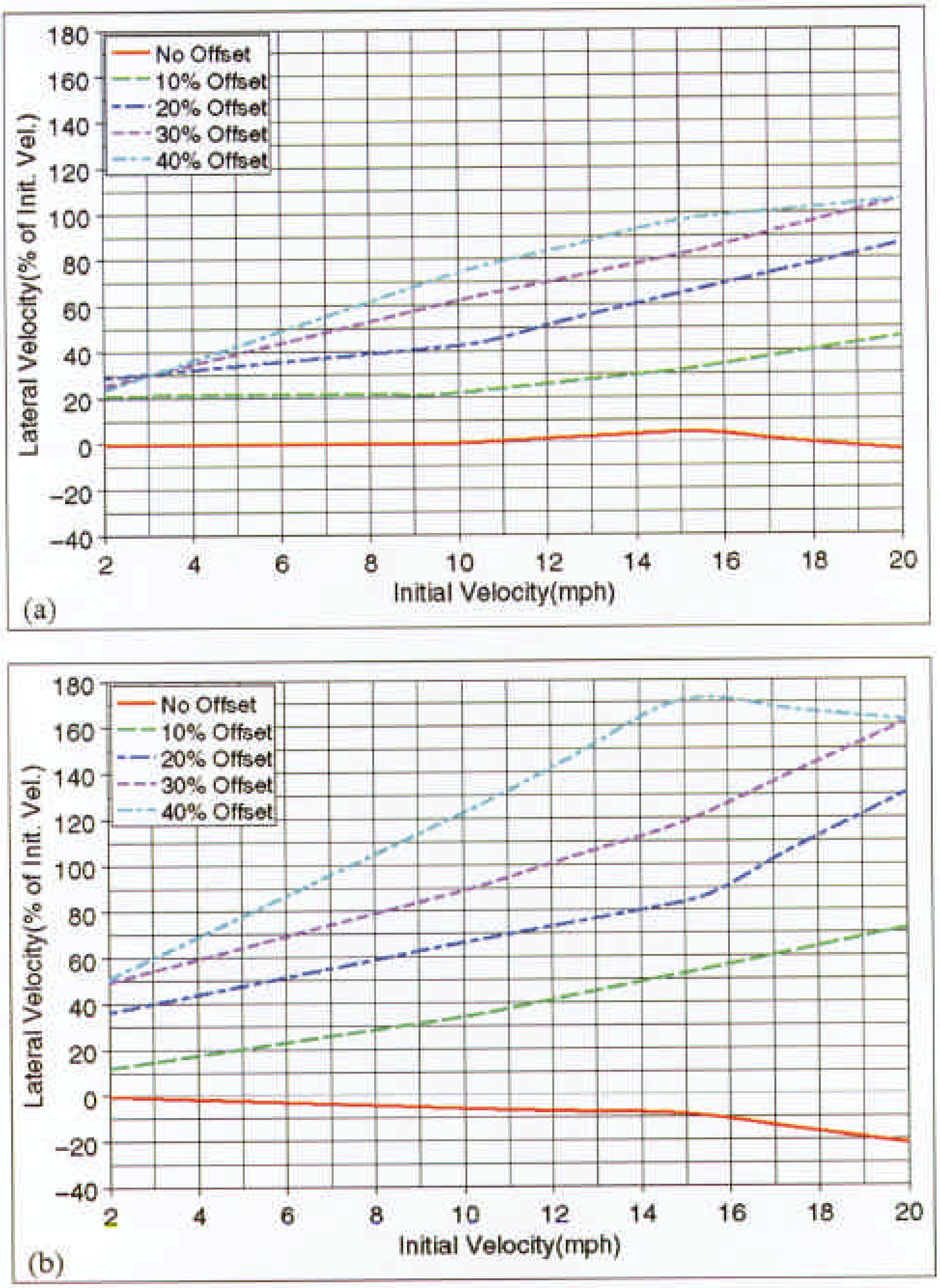

Figure 16. The comparison of lateral velocity relative to the initial velocity.
The ball is 20 cm away from the airbag initially. (a): Lumped modeling; (b): CFD modeling.

CONCLUSIONS

1. Airbag effectiveness for AIS3+ from NASS data:

   A. For unbelted drivers, the airbag has maximum effectiveness in the low velocity range below 20 mph and loses its effectiveness at about 25 mph with the possibility of negative effectiveness.

   B. For belted drivers, the airbag has maximum effectiveness in the low velocity range below 27 mph and its effectiveness reduces for higher delta-V.

2. Airbag effectiveness for fatality from FARS data: For the combined front seated belted and unbelted occupants, the airbag has maximum effectiveness in the low velocity range up to 25-30 mph with reduced effectiveness above that and a possibility of negative effectiveness around 35-45 mph.

3. We have also shown, based on our numerical analysis of the ball-bag model that the effectiveness of airbag is very dependent on occupant sitting position, e.g. initial distance and offset, as well as the initial velocity. For the airbag to be effective at higher crash velocity: 1) airbag should deploy early in the crash, 2) the occupant should be more inline with the airbag. Thus, only in limited conditions, for example a rigid barrier MVSS 208 like test, is the airbag effective in "high" velocity impacts. In addition, the restriction of occupant motion during the crash imposed by restraints other than airbag, e.g. seat belt, can reduce the risk of the airbag and result in more effectiveness of the airbag.

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DISCUSSION

PAPER: **Airbag Effectiveness as a Function of Velocity**

PRESENTER: ***Guy Nusholtz, Daimler Chrysler***

QUESTION: *Richard Kent, UVA*

A quick question since I know it is almost lunch time here. It is a very interesting result. First, I notice you have an effectiveness still positive down at 8 miles per hour from the NASS data which I think is below most airbag firing thresholds. And I am wondering what that says, that looked like that effectiveness would stay positive even at lower velocities, it wasn't even getting close to zero. I wondered if you could comment on that and what that means?

ANSWER: Okay. Let me comment on that and what that means. There are some, there are a number of cases in NASS which go down below 8, so that data does exist. Basically, below 10 is not statistically significant. And the reason that you have that drop is because of a process that we use to develop it. So, you might say, well, really you can't look at below 10 miles an hour although it is consistent with the data. So I would agree that the lower end of that may not be statistically relevant, even though it followed the trend that we saw from the rest of the data.

Q: I mean it's not a popular thing to say this, but maybe very low firing threshold would be okay. Your effectiveness was still fairly high and, in fact, that might get you out earlier at the higher velocities and also help you there?

A: That's absolutely correct.

Q: One other comment that I thought was interesting. You have a negative effectiveness of 30 miles an hour which is 208. I was wondering if you would comment on that. A vehicle would not do better than 208 without an airbag. Can you just comment on that?

A: I think the basic comment is in the 208 condition based on the model analysis we have the airbag is effective. I would expect if you were to crash in 208 if you went into a rigid concrete barrier and you were sitting in the 208 position, you weren't off to the side then the airbag would be effective at that time. But most people do not sit in the 208 position, there isn't a warning in the car that says please assume the 208 position. And there could be offset, that's why we pursued the model. If you look at the test data from 208 or a lot of the other things it looks like the airbag should be very effective. You should be eliminating all the deaths at 30 miles an hour, yet we don't. The other clue to that, if you look at the angle test you can't find that the airbag is effective on the angle test or any of the angle data that you're getting. That really loses effectiveness once you go off of 12 o'clock.

Q: So doesn't that mean we need to move on, move further into the offset testing?

A: Absolutely not. It means you've got the wrong approach in forcing the development of airbags.

Q: *Erik Takhounts, NHTSA*

Have you tried to look using your modeling at the airbag aggressivity with Delta V, increased aggressivity so that by the time of contact the airbag is fully deployed and you see what happens at that time? Because when you increase Delta V airbag you have a shorter time with dummies or whatever, a person is traveling and the airbag is still deploying.

A: Okay. I think I know what your question is, but I am not sure. I'll give you an answer and you can tell me whether I answered your question or not or whether I answered some thing completely different. There are two competing factors. One is as you increase the severity of the crash the airbag will fire a little earlier. But the other competing factor is the occupant will move farther. So as you have a very severe crash, if you get the airbag out in 10 milliseconds you might be able to get the bag in place before the occupant gets to a position where it makes contact. However, if the airbag fires later then the occupant will move into what we would call the deployment zone and then you lose the effectiveness on the airbag.

The question which I didn't present but we've done this study, does the effectiveness zone move closer to the occupant faster than the airbag gets out? And it looks like it does, because you can't get the airbag in place in time at the higher velocities so you lose a little bit of effectiveness.

Q: Another question is have you looked at the injury shift with increased Delta V? Suppose there is a neck injury and with increased Delta V there could be head injuries. Have you looked at that?

A: We looked at it only in terms of we've done a lot of work looking solely at head injuries. Because when we did the initial study that we did we only saw that there was a big effectiveness of the head. We couldn't find a lot of effectiveness in any other areas. So we chose to focus on the head because that's where the result should come out so earlier we just looked at it we saw that the head injuries were being reduced that's where we'd see where the effect is and that's the only thing we looked at.

Q: *Michael Griffiths, Right Site Solutions, Australia*

I am puzzled how you got velocity data out of the Australian fatal accident reporting system because it is just the police reports from each state forwarded into a central register. And as far as I am aware the only velocity data they'd have is the speed zone in which the crash occurred. And the second thing is, >91 to '95 there were very few airbags around Australia.

A: Yes, but we're using NASS data. The Australian data was done on FARS so it's not Australian data, it's done on the FARS. What was reported in the paper is risk of injury and airbag versus airbag effectiveness, so not velocity. What we did is we took that risk in using the NASS data assuming that would be an appropriate risk model and mapped that risk back to velocity. So we took what was published and calculated out what should be the effective velocity given that risk. There's all sorts of mathematical irregularities with doing that and particular problems which could be identified but that was the only way to get a velocity data out of the FARS.